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Review Article

Algal biofuel: A symbol of sustainability in the developmental era

Kavita Tariyal[1], Dhanesh M. Bartwal[1], Seema Bartwal[2]
[1]Department of Applied Sciences & Humanities, THDC Institute of Hydropower Engineering & Technology, Bhagirthipuram, Tehri Garhwal-249001, Uttarakhand, India.
[2]Department of Seed Science & Technology, H.N.B. Garhwal University, Srinagar (Garhwal), Uttarakhand, India.

Corresponding author
Dr. Kavita Tariyal
Email: kavitathdc16@gmail.com

Abstract: In this new era of ecofriendly renewable energy algae have received a lot of attention as a new biomass source. The striking features of algae which set them apart from other biomass sources are that these have a high biomass yield per unit of light and area, can have a high oil or starch content, do not require agricultural area, and fresh water is not essential. Along with this nutrients can be supplied by wastewater and CO_2 by combustion gas. Gasoline, diesel, and jet fuel which are derived by algae seem to hear like the imaginings of any science fiction, but a growing number of researchers, entrepreneurs, investors, academics, and policy makers are doing their best to make them reality. As our reliance on oil in terms of economic, national security, and environmental costs is becoming clearer every day, algae can provide huge quantity of biofuel with negligible environmental impacts. In the light of aforesaid issues, algae are becoming the centre of attention as an optional renewable source of biomass for production of bioethanol, which is grouped under ''Third generation biofuels". Extensive research is being carried out over the last three decades there has been extensive research on algal biofuels production and the use of algae for CO_2 bioremediation. Present review focuses on various types of algal biofuels and their environmental sustainability.
Keywords: algae, bioethanol, biofuel, CO_2 bioremediation, environmental sustainability, renewable energy

INTRODUCTION

It is predicted that the global demand for petroleum will be amplified 40% by 2025 [19]. Persistent use of petroleum based fuels is now extensively documented as unsustainable because of depleting supplies and the contribution of these fuels to the buildup of carbon dioxide in the environment. For environmental and economic sustainability we strongly need renewable and carbon neutral transport fuels [7]. The only way to protect threatening economic conditions from petroleum price shocks is to lower the reliance on petroleum in the economy. Use of alternative fuels can be the most sensible and least disruptive approach to achieve this objective. Oil-crop derived biodiesel which is considered as a potential renewable, carbon neutral alternative to petroleum fuels can act as a solution to the problem of peak oil [14]. But, there are two demerits associated with this approach: first, growing more oilseed crops would displace the food crops grown to nourish mankind. Second, traditional oilseed crops cannot be considered as most efficient source of vegetable oil [9]. The insufficiency of fossil based fuels and an adverse environmental impact produced by the conventional sources of energy has resulted new research work to find the sustainable sources of clean energy. Biofuels are committed to become a worldwide leader in the consumption as well as expansion of renewable energy resources. It is now considered that algae may be helpful to stabilize the present concentration of CO_2 instead of reducing it to a more "healthy" level. Along with this, algae present more characteristics like, biodiesel produced is non toxic, without sulfur, highly biodegradable and relatively less ecological impact if spilled. Algae are skilled in producing about 30 times more oil per acre than corn and soybean crops. Algal biofuel production has not reached at commercial level yet because of the high expenses allied with its manufacture, harvesting and oil extraction but still the technology is progressing with extensive research to find out how microalgae can be utilized as a prime energy source and to make algal oil production commercially feasible.

Algae, especially microalgae are emerging to be the only source of renewable biodiesel that can fit on the global demand for transport fuels [27]. Microalgae use sunlight to produce oils just like the crop plants but they do so more efficiently than the letter [4]. Oil productivity of many microalgae greatly exceeds the oil productivity of the best producing oil crops. Algae are said to yield about 1,200-10,000 gallons of oil/acre, compared to 48 and 18 gallons/acre for soy and corn, respectively [7]. Algae can be grown in ponds or in plastic tanks called bioreactors with little more sun light, heat and water [1]. Above all, algae can be very efficient in absorbing carbon which is generated by fossil fuel power plants which makes it a carbon neutral biofuel [3]. With this one can say that algae can produce a biofuel which can be efficient enough while cleaning up other environmental problems [18]. Present review mainly focuses on the potential of algal biomass

as a source of biofuel, and as environmentally friendlier and renewable transportation fuel.

Algae are uni or multicellular, primarily aquatic, plantlike organisms which require three basic components to grow: sunlight, CO_2 and water. Like plants, algae also use photosynthesis as an important bio-chemical process to convert the energy of sunlight to chemical energy. Algae are known to the world in two forms: Microalgae and Macroalgae. Being more important as biofuel, microalgae are microscopic organisms that grow in salt or fresh water. These can be further divided in four groups, diatoms (Bacillariophyceae), the green algae (Chlorophyceae), the golden algae (Chrysophyceae), and blue-green algae (cyanobacteria). Microalgae have considerable lipid content which can even be very high under certain stress conditions. Microalgae are much efficient in converting solar energy into biomass. The major species of microalgae commercially utilized for the production of biofuel includes *Isochrysis*, *Chaetoceros*, *Chlorella*, *Arthrospira* (*Spirulina*) and *Dunaliella* [7, 26, 27].

DIFFERENT BIOMASS PRODUCTION SYSTEMS FOR MICROALGAE

To produce biomass from microalgae is considered as pricier than that to grow crops. It requires temperature within 20 to 30°C. Despite of daily and seasonal fluctuations in light levels, biofuel production must be reliant on freely accessible sunlight to curtail expenses. Growth medium must be a provider of inorganic elements that constitute the algal cell, including nitrogen, phosphorus, and iron [7, 17]. Growth media are usually low-priced. Biomass of microalgae contains about 50% carbon by dry weight. Large-scale production of microalgal biomass requires continuous culture during daylight. In this method, fresh culture medium is fed at a constant rate and the same quantity of microalgal broth is withdrawn continuously [17]. Considerably, two main methods are opted for the large-scale production of algal biomass-

1. *Raceway ponds* [17, 30].
2. *Tubular photobioreactors* [17, 23].

Raceway Pond method for algal biomass production

A raceway pond is made up of a closed loop recirculation channel in which mixing and circulation are produced by a paddlewheel. Flow is maintained around bends by baffles which are placed in the flow channel. Raceway channels are built by concrete or compacted earth which may be covered with white plastic. The culture is fed continuously during daylight in front of the paddlewheel where the flow begins. On the completion of the circulation loop, broth is harvested behind the paddlewheel which is operated all the time to prevent sedimentation [7]. This method of culturing microalgae has being practiced since 1950s. It needs a lot of extensive experience for the operation and engineering of raceways. It is documented that the largest raceway-based biomass production facility occupies an area of about 4,40,000 m^2 [27]. Cooling can be achieved only by evaporation process in raceway ponds in which temperature fluctuates within a diurnal cycle and with seasonal change. Due to significant water losses to the atmosphere which is because of evaporation, raceways use CO_2 to a much lesser extent as compared to photo bioreactors. Moreover, due to contamination with unwanted algae and microbes which feed on algae the productivity decreases. With this the biomass concentration remains low because raceways are poorly mixed and are not able to uphold an optically dark zone [7]. It is apparent that raceway ponds are less expensive than photo bioreactors, because they cost less to build and operate.

Photo bioreactors: the next option

Photo bioreactors allow essentially single-species culture of microalgae for extended durations which is generally not seen in the case of open raceway ponds. Various researchers have documented the successful production of large quantities of microalgal biomass using photo bioreactors [5, 17, 22]. The structural composition of a photo bioreactor is entirely different from raceways in which there is an array of straight transparent tubes called solar collector usually made of plastic or glass. In these solar collector tubes, which generally have a diameter of 0.1 m or less, the sunlight is captured. It is necessary to limit the tube diameter because light should not penetrate too deeply in the dense culture broth which is essential for ensuring high biomass productivity in the photo bioreactor. Microalgal broth is distributed from a reservoir to the solar collector and back to the reservoir. Continuous culture operation is used, as explained above. In this whole procedure the main objective of the manufacturing solar collector is to maximize sunlight capture which is one of the most indispensible steps. The ground beneath the solar collector is generally painted white, or covered with white sheets of plastic, to increase reflectance, or albedo [7]. To prevent the sedimentation of biomass in these tubes the highly turbulent flow is maintained which is produced using either a mechanical pump or a gentler airlift pump. Mechanical pumps can damage the biomass but are easy to design, install and operate. Airlift pumps have been used quite successfully.

Photo bioreactor and raceway ponds for production of microalgal biomass can be compared with the help of Table 1. This comparison is based on an annual production level of 100 t of biomass in both cases. If the losses to atmosphere are assumed as constant or unnoticed, then both production methods consume an identical amount of CO_2. Photo bioreactors yield much more oil per hectare as compared to raceway ponds and this is because the volumetric biomass productivity of photo bioreactors is more than 13-fold greater in comparison with raceway ponds. Both raceway and photo bioreactor production methods are technically practicable.

Table 1: Comparison of photo bioreactor and raceway production methods [7].

Variable	Photo bioreactor	Raceway ponds
Annual biomass production (kg)	100,000	100,000
Volumetric productivity (kg m^{-3} d^{-1})	1.535	0.117
Areal productivity (kg m^{-2} d^{-1})	0.048	0.035
Biomass concentration in broth (kg m^{-3})	4.00	0.14
Dilution rate (d^{-1})	0.384	0.250
Area needed (m^2)	5681	7828
Oil yield (m^3 ha^{-1})	136.9	99.4
Number of units	6	8

Production of biofuel from microalgae

Algae have proved itself as one of the most efficient resources when it comes to renewable raw material for biofuels. The vegetable oil from algae can be harvested directly (by the esterification process) or it can be refined into a variety of biofuels, which include renewable diesel and jet fuel. The extracted carbohydrates from algae can be fermented to make additional biofuels, including ethanol and butanol, as well as other products such as plastics and biochemicals. Microalgal biomass can be used for pyrolysis oil or combined heat and power generation. Renewable diesels derived from microalgae and jet fuels can directly replace petroleum fuels without modification of engines. Algae derived fuels generally fulfill all the demands and conditions for the petroleum fuel they replace. Algae are such type of renewable resources for biofuels that can be grown on non-arable lands consuming saltwater or brackish water. One of the most promising and significant benefit of algal consumption for producing biofuels is that there is no need of using displaced farmland which was used for growing food sources. Algae have a fundamental ability of capturing CO_2 and transforming it into organic energy by the process called photosynthesis. Algae can be considered a biomass resource which is without carbon footprint. Even if there are different technologies described in greater detail, this is considered as the principal energy process for aquatic biomass. Due to their rich photosynthetic activity and efficacy to generate lipids, a biodiesel feedstock, microalgae have engrossed the attention of various researchers. Macroalgae do not generally contain lipids and are being considered for the natural sugars and other carbohydrates they contain, which can be fermented to produce either biogas or alcohol-based fuels.

Trans-esterification: a process to convert oil to biodiesel

There are many documented microalgae which are remarkably rich in oil and can be transformed to biodiesel using existing technology [31]. As compared to the best oil-producing crops, Microalgal biodiesel has shown tremendous potential to be capable of completely displacing petroleum based transport fuels without any adverse impacts on food supplies and other agricultural products. Parent oil used in making biodiesel consists of triglycerides in which three fatty acid molecules are esterifies with a molecule of glycerol. The basic reaction of making biodiesel involves triglycerides which are reacted with methanol in a reaction which is popularly known as transesterification or alcoholysis. Transesterification produces methyl esters of fatty acids that are biodiesel and glycerol (fig 1).

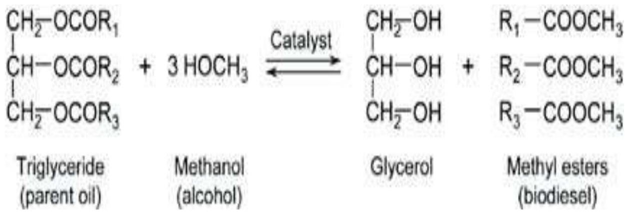

Fig 1: Transesterification reaction [10].

Fermentation of microalgal biomass for ethanol production

Alcoholic fermentation is considered one of the most important processes of the glycolytic pathway and it consists in its anaerobic conversion to ethanol and CO_2, in two steps. In the first step, pyruvate is decarboxylated by the enzyme pyruvate decarboxylase, releasing CO_2 and forming acetaldehyde, which is then reduced to ethanol by the enzyme alcohol dehydrogenase. The fermentation can be represented by the equation [16].

$$C_6H_{12}O_6 + 2ADP + 2Pi \rightarrow 2C_2H_5OH + 2CO_2 + 2ATP + 2H_2O$$

The principal reason and benefit of using ethanol as a fuel is that it reduces level of lead, sulfur, carbon monoxide and particulates; which are considered potential air pollutants. Additionally, there is the worldwide advantage of reducing CO_2 emissions. With the escalating requirement of fossil fuel replacements the USA, Europe and other states have started

considering the substitution of petrol with ethanol [32]. The fundamental principle acting behind ethanol production by microalgal biomass consists in the cultivation of microorganisms, harvesting of cells, preparation of biomass, fermentation, and extraction process of ethanol. The microalgal biomass can be prepared through mechanical equipment or enzymes that dissolve the cell walls, making the carbohydrates more obtainable, as well as breaking down large molecules of carbohydrates. After cell breakage, the yeast *Saccharonmyces cerevisiae* is supplemented to the biomass and with this the fermentation begins. In this way, the sugar is converted to ethanol by yeasts. For the purification of ethanol, yeast is added.

Biogas production from microalgal biomass

Biogas is produced from the anaerobic digestion of organic matter, consisting chiefly of 55.0–65.0% methane (CH_4), 30.0–45.0% carbon dioxide (CO_2), traces of hydrogen sulfide (H_2S) and water vapor [2]. The process of anaerobic digestion involves three chronological stages: hydrolysis, fermentation and methanogenesis. The anaerobic digestion process is optimized when one uses compounds with moisture content between 80.0% and 90.0%, and the use of microalgal biomass is highly appropriate [2]. According to a case study done in Southern Brazil, the biomass from *Spirulina* LEB 18 grown in an 18.0 m^3 raceway-type photobioreactor under environmental conditions was used as a substrate for biogas production in a semi-continuous anaerobic bioreactor. The biogas content obtained in the methane was 77.7% [8].

Reasons behind taking algae as a substrate

Various reasons explain why have proved itself as a more efficient, environmentally sound, and sustainable biofuel. These reasons are:

1) Algae are having very high photon conversion efficiency;
2) Algae can manufacture and accumulate large quantities of carbohydrate biomass for bioethanol production even from inexpensive raw materials;
3) Algae are capable enough to bear and utilize considerably higher levels of CO_2;
4) Algae are having such a vast group comprising several thousand diverse species which makes them enable to get chosen as per the desired species according to the working environment;
5) Algae are skilled of producing high yields of stored material; and
6) Algal cells can be harvested within a short span of time as compared to other feedstocks.

Algae: A footstep towards sustainability

Varying global climate scenario and day by day depleting fossil fuels with mounting price of petroleum-based fuels have forced researchers to explore alternative, sustainable, renewable, efficient and cost-effective energy sources with lesser carbon footprints [20]. Even if the growth of food crops for biofuel production may be able to tackle environmental issues, it has produced qualms about its potential impact on food supply and security. There is an urgent demand at global level for alternative and sustainable biofuel which is not produced at the cost of food-based feedstock, instead it should be harnessed from the biomass which neither need any specific crop area nor gives any harm to food security. As compared to other feedstocks, algae are capable of providing a high-yield source of biofuels without compromising food supplies, rainforests or arable land [29]. Bio-diesel is any biomass-derived oil which is utilized as diesel fuel substitute. The biggest advantage of using algal biofuel which separates it from other alternative transportation fuels is that it can be used in existing diesel engines without modification, and can be blended in at any ratio with petroleum diesel. Biodiesel have been noticed as a non-emitter of particulate matter, CO (carbon monoxide), hydrocarbons, and SOx (oxides of sulphur) while performing. However, it is recorded in some cases of biodiesel that emissions of NOx (oxides of nitrogen) are higher. Bio-diesel almost eliminates the harmful black soot emissions which are coupled with diesel engines. Also, the number of total particulates emitted is much lower in biodiesel. Other environmental benefits of bio-diesel worth concerning are that it is highly biodegradable and is effective in reducing emissions of air toxics and carcinogens (relative to petroleum diesel). Enough to say that apart from several mentioned environmental benefits, algal biofuel have proved to be very promising and sustainable alternate fuel products. Usage of bio-diesel will make a balance to be sought between agriculture, economic development, and the environment [13].

Biosequestration of CO_2 by algae

One important term should be mentioned here which is referred to as Biosequestration of CO_2 by algae in which CO_2 can be sequestered or immobilized through filtering or other mechanical/chemical processes and subjected for long-term storage to avoid release into the atmosphere. The "Aquatic Species Program" is a project which is involved in the investigating of possibilities of using algae to sequester CO_2 emitted from coal power plants [24]. Microalgae are considered to be more efficient in photosynthesis as compared to C4 plants (those plants that form four carbon stable intermediates in the photosynthetic process; generally associated with agricultural and large terrestrial plants). Also these have faster proliferation rates, wider tolerance to extreme environments, and are having higher potential for intensive cultures. Greenhouse gas mitigation can be done by simply removing the CO_2 from stack gases and after that long term sequestration of CO_2 by microalgae ponds. There is no difficulty in locating any huge raceway algal farm because it can be installed anywhere even nearby power plants. The bubbling of flue gas from a power plant into these ponds helps in recycling of waste CO_2 from the

burning of fossil fuels. The idea of establishing a coal-fired power plant along with an algal farm provides an excellent approach to GHG mitigation of the CO_2 from coal combustion into a useable liquid fuel. With this, the approach of sustainable development can be achieved which is the demand of the era. In this way microalgae technology can be helpful in energy harnessing from coal combustion and simultaneously it reduces carbon emissions by recycling waste CO_2 from power plants into clean-burning bio-diesel [13].

Conclusion

Microalgae-based carbon sequestration technologies are not only efficient in covering the cost of carbon sequestration but also manufacture environment-friendly biodiesel. Algae have achieved a renewed interest as an alternative and renewable source of energy in the current period of towering oil prices, diminishing world oil reserves, and the environmental deterioration associated with fossil fuel consumption and green house gases emission. Algae derived biofuels have minute impact on the world's food supply as compared to conventional biofuel producing crops. Microalgal biodiesel presents an excellent example of technically viable and carbon–neutral renewable alternatives. Conversion of algal biomass into biofuel can perform better developmental activities along with climate co-benefits. Utilization of the bio-refinery concept in raceway ponds engineering can further lower the production cost. It is the only renewable biofuel that can effectively and completely replace petroleum derived liquid fuels from the market. If the microalgae based bio-refinery concept can be adapted to a developing country like ours, it could become a greatly distributed source of fuel oil and may help to make us self-sufficient and make our economy positively accelerated. In the present scenario, algal biomass is a key link between energy, local environment and climate change and further research are necessary to unlock full potential of algae.

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